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Evaluating Product Machinability for Concurrent Engineeering[*]

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Abstract

Decisions made during the design of a machined part can significantly affect the product's cost, quality, and lead time. Thus, in order to address the goals of concurrent engineering, it is important to evaluate the machinability of the proposed design, so that the designer can change the design to improve its machinability.

To determine the machinability of the part, all of the possible alternative ways to machine the part should be generated, and their machinability evaluated. This chapter describes the techniques we have developed to do this automatically.

The information provided by these techniques will prove useful in two ways: (1) to provide information to the manufacturing engineer about alternative ways in which the part might be machined, and (2) to provide feedback to the designer identifying problems that may arise with the machining.

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1 Introduction

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time. Such considerations have led to the idea of identifying design elements that pose problems for manufacturing and quality control, and providing feedback to the designer so that the designer can change the design to improve its manufacturability [49, 7].

In the case of machined parts, a part is often considered as a collection of machinable features [14, 4, 39, 37, 13, 41]. If we can evaluate the machinability[1] of these features, then the information produced by such an analysis can be used to provide feedback to the designer identifying problems that may arise with the machining. For example, if it is not possible to produce some feature to within the desired tolerances, then the designer may need to change the design accordingly. Thus, some of the goals of concurrent engineering can be addressed through the following steps:

Step 1. generate a feature-based model for the object, i.e., an interpretation of the object as a collection of machinable features;

Step 2. for these features, select appropriate machining processes and process parameters, and evaluate whether the selected processes and parameters will be capable of producing the object to within the desired tolerances, and if so, what the associated machining costs and times will be.

We will now discuss two major issues that arise in performing the above steps.

First, what tolerances and surfaces finish a machining process can create will depend on the feature geometry and the machine tool [25, 8, 9, 23, 44]. But in addition, variations in hardness in the material being machined cause random vibration during machining [56, 57, 59, 52, 53, 54, 55], and this vibration is one of the major factors affecting the quality of the resulting surface.

Second, existing approaches for obtaining machinable features from a CAD model [2, 12, 50, 35, 38, 48, 15, 40, 47, 42, 43] normally produce a single interpretation of the part as a collection of machinable features. However, there can be several different interpretations of the same part as different collections of machinable features—or equivalently, different sequences of machining operations for creating the same part [11, 48, 21, 19]. To determine the machinability of the part, all of the alternative interpretations should be generated and examined.

For example, in the machined part shown in Fig. 1, there are several different ways to interpret the hole h_1 and its relation to the slot s_2 and the shoulders s_1 and s_3. These interpretations correspond to different sequences of machining operations. For example, interpretation (a) corresponds to making h_1 after s_1 and s_2, interpretation (b) corresponds to making h_1 after s_1 but before s_2, and so forth. Depending on the feature geometry, tolerance requirements, surface finish requirements, and process capabilities, one or another of these interpretations will be preferred. Here are a few of the tradeoffs involved:

- Interpretations (e)-(h), in which the two holes are made in a single step, produce the tightest concentricity on h_1 and h_2. Thus, one of these interpretations may be necessary if the concenctricity tolerance is tight.

[1] By the machinability of a part, we mean how easy it will be to achieve the required machining accuracy. This is somewhat broader than the usual usage of "machinability."

- If l_3 is large, then interpretations (e)–(h) may require special tooling. Thus, if the concentricity is not tight and l_3 is large, then one of (a)–(d) may be preferable.
- If interpretations (e)–(h) don't require special tooling, then they have the advantage that they minimize the number of setups. Among these interpretations, (h) has the smallest number of tool changes; but (e) has the smallest tool travel distance.
- Interpretation (a) has the advantage that it incurs the smallest amount of wear on the drilling tool. But if l_1 is small, then interpretation (a) may cause excessive workpiece vibration.

To address the issued described above, we are developing a system to generate and evaluate machining alternatives. Sections 2 describes our work on how to generate feature interpretations, and Section 3.2 describes our work on how to evaluate their machinability. Section 4 describes research issues that are currently being addressed, and Section 5 contains concluding remarks.

2 Generating Feature Interpretations

For obtaining machinable features from a CAD model (such as a boundary representation), there are three primary approaches. In *human-supervised feature recognition*, a human user examines an existing CAD model to determine what the manufacturing features are [2]. In *automatic feature recognition*, the same feature recognition task is performed by a computer system [12. 50, 35, 38, 48]). In *design by features*, the designer specifies the initial CAD model in terms of various form features which translate directly into the relevant manufacturing features[15, 40, 47, 42, 43]).

All three of these approaches will normally produce a single interpretation of the part as a collection of machinable features. However, because of interactions among features, there can be several different interpretations of the same part as different collections of machinable features—or equivalently, different sequences of machining operations for creating the same part [11, 48, 22. 21, 19]. To determine the machinability of the part, all of the alternative interpretations should be generated and examined.

To generate alternate interpretations of a part as a collection of machinable features, we have been developing an algebra of feature interactions [21, 32. 19, 20, 17, 18]. Given a set of features describing a machinable part, other equally valid interpretations of the part can be produced by performing operations in the algebra.

Mathematically, an algebra consists of a domain D, along with binary operations defined on members of D. The domain of the feature algebra consists of the set of "all possible machinable features", along with operations such as truncation and maximal extension as described below.

Since each machining operation removes a volume of material, we want a "machinable feature" to be a 3-dimensional solid corresponding to the volume of material that is removed. In addition, some portions of the surface of a feature are *blocked*, i.e., they separate air from metal, and some are *unblocked*, i.e., they separate air from air. Thus, we define a *feature* to be a pair $F = (S, P)$, where S is any compact, regular, semi-analytic set [36], and P is any partition of $b(S)$ into regular semi-analytic subsets, each of which is labeled as "blocked" or

"unblocked". The domain $\mathcal{F}$ of the feature algebra is the set of all pairs (S, P) satisfying the above definition.

When two features $x, y \in \mathcal{F}$ are adjacent, we can define two operations:

$$\begin{array}{ll} E(x,y): & \text{the maximal extension of } x \text{ into } y; \\ T(x,y): & \text{the truncation of } x \text{ by } y. \end{array}$$

In the general case, the definitions of these operations are mathematically complex, so for brevity we omit them here (the reader is referred to [19] for the details). However, Fig. 2 illustrates the definition of the maximal extension operator on a simple example: the maximal extension $E(h_1, s_2)$ of the hole h_1 into the slot s_2, where h_1 and s_2 are as given in Fig. 1. As shown in Fig. 2, one takes the "infinite extension" $I(h_1, p)$, where p is the patch bounding one end of h_1; and truncates $I(h_1, p)$ where it hits the far end of s_2.

From the definitions of the algebraic operators, we have proved various mathematical properties (associativity, etc.), which can be used to predict that various combinations of operators will produce the same feature. We have developed a prototype version of a feature interpretation system making use of these properties which, given an interpretation of an object (i.e., a set of features), uses state-space search techniques [33] to generate all of other interpretations of the same object that result from applications of the algebraic operators. For example, Fig. 3 shows the state space produced for operations on h_1, h_2, s_1, s_2, and s_3.

3 Process Selection and Machinability Evaluation

Given an interpretation of the object as a collection of machining features, we need to evaluate the various possible machining operation sequences for producing these features, to see whether or not any of them can satisfactorily achieve the design specifications. As described below, this involves two steps: (1) select candidate operation sequences, and (2) evaluate them.

3.1 Process Selection

For each feature, we need to select machining operations and associated cutting parameters. Sometimes a feature can be created by a single machining operations (e.g., drilling or face milling), and other times it will require a sequence of operations (e.g., drill then bore then hone, or rough-face-mill then finish-face-mill). Also, in some cases there can be more than one sequence of machining operations that can create the feature geometry and also satisfy the tolerance requirements. Cutting parameters are selected based on past experience or handbook recommendations. Sometimes available machining facilities also affect the choice of cutting parameters.

Due to accessibility [31] and setup constraints [11], the set of features that comprise an object cannot necessarily be machined in any arbitrary sequence. Instead, these constraints will require that some features be machined before or after other features. However, for a given set of features, usually there will be more than one machining operation sequence capable of creating it. For example, in the bracket shown in Fig. 1, consider Interpretation 1 of Fig. 3. In this interpretation, the two holes h_1 and h_2 must be made after the two shoulders s_1 and s_2 and the slot s_3. But there are two possible orderings for making h_1 and

h_2, and six possible orderings for making s_1, s_2, and s_3, so Interpretation 1 gives us twelve possible orderings in which to make the features.

Most knowledge-based systems for automated process selection been rule-based (e.g., see [5, 26, 1, 10]). Our process selection system, although knowledge-based, is based on a different approach. To represent and use problem-solving information for process selection, we use a hierarchical abstraction technique which we call hierarchical knowledge clustering. This approach has implemented in a system called SIPS, and later in a more sophisticated system called EFHA [28, 29, 30, 27, 26]. These systems have been used both in the AMRF project at the National Institute for Standards and Technology [3, 2], and at Texas Instruments [30, 26].

In SIPS and EFHA, knowledge about machining processes is organized in a taxonomic hierarchy. As shown in Fig. 4, each node of the hierarchy is a frame which represents a class of machining processes such as "milling" or "hole-create-process". These frame contain knowledge about the intrinsic capabilities of various machining processes. Given the description of a machinable feature, SIPS and EFHA use the information in the frame hierarchy to guide a state-space search to find sequences of processes capable of creating the feature.

For example, in Fig. 5, SIPS has been given the task of making a hole. By doing a state-space search, it has determined that the best sequence of machining operations for making the hole consists of a twist-drilling operation followed by a rough-boring operation. If asked to continue, SIPS would eventually find each of the sequences of machining processes capable of creating the hole.

Researchers at Texas Instruments have extended SIPS and EFHA's knowledge bases to include information which enables them to select cutting tools and compute feed rates and cutting speeds.

3.2 Machinability Evaluation

Given a candidate operation sequence, the machining data for that sequence, the feature's dimensions and tolerances, and the workpiece material, we want to evaluate whether or not it can satisfactorily achieve the design specifications. The capabilities of the machining process depend on the following factors:

1. The machining system parameters, such as the feed rate, cutting speed, depth of cut, and structural dynamics. Their effects on the process capabilities can be modeled and evaluated deterministically [25, 6, 8, 9, 16, 23, 34, 44, 45, 46, 51].

2. The natural and external variations in the machining process. For example, variations in hardness in the material being machined cause random vibration, which is one of the major factors affecting the surface quality. Such variations are unavoidable in practice, and are best dealt with statistically. This introduces a margin of error into our calculations of the process capabilities. The margin of error needs to be large enough that product quality is maintained, and yet small enough that the cost of the machining process is manageable [56, 57, 59, 52, 53, 58, 24, 54, 55].

We have developed a computer-based system for machinability evaluation, which is capable of determining the achievable machining accuracy such as surface finish, variation of dimensional sizes, and roundness and straightness of rotational surfaces. This system is built on an integration of machining science, materials science, and metrology. It produces a model

of the surface texture formed during machining, and displays a graphic image to aid in visualization. Currently, it can estimate the achievable machining accuracy of four machining processes: turning, boring, drilling, and end milling.

The basic methodology of the evaluation system is shown in Fig. 6. The input consists of the cutting parameters for the selected machining process, and the basic properties of the workpiece material. Through simulation of the variations in cutting force based on the cutting mechanics and prediction of the tool vibratory motion during machining, the system produces a simulation of the topography of a machined surface, such as the one shown in Fig. 7.

Based on this information, the system assesses the machinability of the feature to be produced by the machining process. For example, as shown in Fig. 8, from the simulated surface topography of a hole, the system can take a cross-section perpendicular to the hole's axis and calcuate the maximum and minimum diameters, in order to determine the hole's dimensional tolerances. As shown in Fig. 9, it can take a cross-section parallel to the hole's axis in order to calculate the hole's straightness. In Fig. 9, the confidence band explicitly defines the achievable tolerance for the cylinder being machined.

This system has been tested by research institutions such as the National Institute of Standards and Technology (in the Precision Engineering Division and the Ceramics Division). It is being used by several industries, including the Ford Center for Research and Development and Allied Signal Corp., for evaluating the dimensional accuracy and surface finish quality during the machining of cylindrical surfaces [56, 57, 52, 53].

4 Research Issues

4.1 Generating Alternative Feature Interpretations

In order to produce all of the alternative feature interpretations relevant for machining, some additional operators are needed in the feature algebra. We are developing definitions of these operators. In addition, some of the interpretations currently produced by the current operators are useless in terms of actual manufacturing practice, and we are modifying the feature interpretation system to discard such interpretations. For example, in Fig. 1, suppose the ratio $l_3/d < 2$. Then we will never drill from both sides, so any interpretations that require drilling from both sides should be eliminated, unless some very specific manufacturing requirements dictate otherwise.

We are developing methods for assigning tolerance requirements each new feature produced by the feature algebra. For example, in Fig. 1, suppose the diameter specification for interpretation (a) is $\phi 10 + 0.20$, and that the length of interpretation (b) is twice that of interpretation (a). During the manufacturing process, in most cases a looser diameter specification for interpretation (b) (such as $\phi 10 + .5$) would be sufficient to achieve the diameter specification of $\phi 10 + .20$ for interpretation (a). If we use $\phi 10 + .20$ for interpretation (b), then in most cases we are using a tighter tolerance specification than is actually required, resulting in an unnecessarily high machining cost.

The dimensions of the feature to be machined sometimes depend on the direction from which the tool will be approaching. For example, consider interpretations (b) and (c) of Fig. 1, which are reproduced in Fig. 10. In interpretation (b), we must machine a hole of length $l_0 + l_1$. However, in interpretation (c), we do not need to machine a hole of length l_2.

Instead, as shown in Fig. 10, the length may be between l_1 and l_2. We are working out the mathematics governing the relationships between the features and the machining operations.

4.2 Machinability Evaluation

Evaluating the machinability of alternative interpretations of an object will require repeated calls to the machinability evaluation module. To reduce the total time required for that task, we intend to augment the machinability evaluation system to provide means for fast approximate estimation of machining economics indices. This capability will quickly eliminate those feature interpretations that are infeasible in view of common manufacturing practice.

We intend to extend the system to make it capable of evaluating additional machining processes, such as face milling and grinding, and additional geometric tolerance parameters, such as the cylindricity of rotational surfaces and the flatness of planar surfaces.

Currently, the machinability evaluation is based on a model of tool deflection but not workpiece deflection. To make the machinability evaluation more sophisticated, we intend to incorporate into the machinability evaluation the effects of the static and dynamic deflection of the workpiece during machining, as well as the structural dynamics of the machine tool.

5 Conclusions

Decisions made during the design of a product can have significant effects on product cost, quality, and lead time. This has led to the evolution of the philosophy of concurrent engineering, which involves identifying design elements that pose problems for manufacturing and quality control, and changing the design, if possible, to overcome these problems during the design stage.

We anticipate that our research will have direct impact on the above issue. The analysis performed by our system will enable us to provide feedback to the designer by identifying what problems will arise with the machining. By comparing the tolerances achievable by various machining operations with the designer's tolerance requirements, we should be able to suggest to the designer how much the design tolerances should be loosened in order to make the feature easier (or possible) to machine.

In addition, for features whose tolerance and surface finish requirements are more easily achieved, the analysis will typically provide several alternative machining operations capable of achieving them. Such information will be useful to the manufacturing engineer in developing alternative plans for machining the part if the preferred machine tools or cutting tools are unavailable.

We anticipate that this work will provide a way to evaluate new product designs quickly in order to decide how or whether to manufacture them. Such a capability will be especially useful in flexible manufacturing systems, which need to respond quickly to changing demands and opportunities in the marketplace.

References

[1] S.L. Brooks and K.E. Hummel. Xcut: A rule-based expert system for the automated process planning of machined parts. Technical Report Technical Report BDX-613-3768,

Bendix Kansas City Division, 1987.

[2] P. Brown and S. Ray. Research issues in process planning at the National Bureau of Standards. In *Proc. 19th CIRP International Seminar on Manufacturing Systems*, pages 111–119. June 1987.

[3] P. F. Brown and C. R. McLean. Interactive process planning in the AMRF. In *Symposium on Knowledge-Based Expert Systems for Manufacturing at ASME Winter Annual Meeting*, pages 245–262. Anaheim, CA, Dec. 1986.

[4] Butterfield, Green, Scott, and Stoker. Part features for process planning. Technical Report R-86-PPP-01, Computer Aided Manufacturing International, November 1986.

[5] T. C. Chang and R. A. Wysk. *An Introduction to Automated Process Planning Systems.* Prentice-Hall, Englewood Cliffs, NJ, 1985.

[6] G. Chryssolouris, M. Guillot, and M. Domroese. A decision making approach to machining control. *Transactions of the ASME, Journal of Engineering for Industry*, 110(4):397–398, November 1988.

[7] M. R. Cutkosky and J. M. Tenenbaum. Providing computational support for concurrent engineering. *Systems Automation, Research and Applications*, to appear 1991.

[8] R.E. DeVor, W. Kline, and W. Zdeblick. A mechanistic model for the force system in end milling with application to machining airframe structures. In *Proceedings of NAMRC*, volume 8, pages 297–303, 1980.

[9] R.E. DeVor, J. Sutherland, and W. Kline. Control of surface error in end milling. In *Proceedings of the NAMRC*, volume 11, pages 356–362, 1983.

[10] I. Ham and S. Lu. Computer aided process planning, the present and the future. *Annals of CIRP*, 37(2), 1988.

[11] C. Hayes and P. Wright. Automatic process planning: using feature interaction to guide search. *Journal of Manufacturing Systems*, 8(1):1–15, 1989.

[12] Mark Richard Henderson. *Extraction of Feature Information from Three Dimensional CAD Data.* PhD thesis, Purdue University, May 1984.

[13] K. E. Hummel. The role of features in computer-aided process planning. In *Proc. CAMI Features Symposium*, number P-90-PM-02, pages 285–320, August 9–10 1990.

[14] K.E. Hummel and S.L. Brooks. Symbolic representation of manufacturing features for an automated process planning system. In *Knowledge-Based Expert Systems for Manufacturing Symposium*, number BDX-613-3580, December 1986.

[15] N. C. Ide. Integration of process planning and solid modeling through design by features. Master's thesis, University of Maryland, College Park, MD, 1987.

[16] S.G. Kapoor, G. Zhang, and L. Bahney. Stability analysis of the boring process system. In *Proceedings of the NAMRC*, volume 12, pages 454–459, 1984.

[17] R. Karinthi and D. Nau. Using a feature algebra for reasoning about geometric feature interactions. In *IJCAI-89*, August 1989.

[18] R. Karinthi and D. Nau. Using algebraic properties and boolean operations to compute feature interactions. In *AAAI Spring Symposium*, Stanford, 1989.

[19] R. Karinthi and D. Nau. An algebraic approach to feature interactions. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 1992. To appear.

[20] R. Karinthi and D. S. Nau. Algebraic feature translation and applications to concurrent design. In *Workshop on Concurrent Engineering Design*, Detroit, Michigan, August 1989.

[21] Raghu Karinthi and Dana Nau. Geometric reasoning using a feature algebra. In F. Famili, S. Kim, and D. S. Nau, editors, *Artficial Intelligence Applications in Manufacturing.* AAAI Press/MIT Press, to appear 1991.

[22] Raghu Ram Karinthi. *An Algebraic Approach to Feature Interactions.* PhD thesis, Computer Science Department, University of Maryland, December 1990.

[23] W. Kline, R. DeVor, and I. Shareef. The prediction of surface accuracy in end milling. *Transactions of the ASME, Journal of Engineering for Industry*, 104:272–278, 1982.

[24] S. C-Y. Lu and G.M. Zhang. A combined inductive learning and experimental design approach to manufacturing operation planning. *Journal of Manufacturing Systems*, 9(2):103–115, 1990.

[25] Machinability Data Center. *Machining Data Handbook.* Metcut Research Associates, Cincinnati, Ohio, second edition, 1972.

[26] D. S. Nau. Automated process planning using hierarchical abstraction. *TI Technical Journal*, pages 39–46, Winter 1987. Award winner, Texas Instruments 1987 Call for Papers on AI for Industrial Automation.

[27] D. S. Nau. Hierarchical abstraction for process planning. In *Second Internat. Conf. Applications of Artificial Intelligence in Engineering*, 1987. SRC Tech Report 87-105.

[28] D. S. Nau and M. Gray. SIPS: An application of hierarchical knowledge clustering to process planning. In *Symposium on Integrated and Intelligent Manufacturing at ASME Winter Annual Meeting*, pages 219–225, Anaheim, CA, Dec. 1986.

[29] D. S. Nau and M. Gray. Hierarchical knowledge clustering: A way to represent and use problem-solving knowledge. In J. Hendler, editor, *Expert Systems: The User Interface*, pages 81–98. Ablex, Norwood, NJ, 1987.

[30] D. S. Nau and M. Luce. Knowledge representation and reasoning techniques for process planning: Extending SIPS to do tool selection. In *19th CIRP International Seminar on Manufacturing Systems*, 1987. SRC Tech Report 87-106.

[31] D. S. Nau, G. Zhang, and S. K. Gupta. Generation and evaluation of alternative operation sequences. In *Submitted for publication*, 1992. Available as SRC TR 92-20.

[32] Dana S. Nau and Raghu R. Karinthi. Handling feature interactions in concurrent design and manufacturing. In *Proc. Manufacturing International 1990*, August 1990.

[33] N. J. Nilsson. *Principles of Artificial Intelligence.* Tioga, Palo Alto, 1980.

[34] S. Pandit, T. Subramanian, and S. Wu. Modeling machine tool chatter by time series. *Transactions of the ASME, Journal of Engineering for Industry*, 97:216–219, 1975.

[35] J. M. Pinilla, Finger S., and F. B. Prinz. Shape feature description and recognition using an augmented topology graph grammar. In *Proceedings of the NSF Engineering Design Research Conference*, June 1989.

[36] A. G. Requicha and H. B. Voelcker. Boolean operations in solid modeling boundary evaluation and merging algorithms. *Proceedings of the IEEE*, 73(1):30–44, 1985.

[37] Mary Rogers. Features modeling. Technical Report R-89-GM-02, CAM-I, July 1989.

[38] Hiroshi Sakurai and David C. Gossard. Recognizing shape features in solid models. *IEEE Computer Graphics and Applications*, September 1990.

[39] J. Shah, P. Sreevalsan, M. Rogers, R. Billo, and A. Mathew. Current status of feature technology. Technical Report R-88-GM-04.1, CAM-I Inc., 1988.

[40] J. J. Shah and M.T. Rogers. Functional requirement and conceptual design of the feature based modeling system. *Computer Aided Engineering Journal*, 7(2):9–15, February 1988.

[41] Jami Shah. Philosophical development of form feature concept. In *Proceedings of Feature Symposium*, number P-90-PM-02, Woburn, Boston, MA, August 1990.

[42] Jami Shah, Mary Rogers, and Palat Sreevalsan. Conceptual design of feature based modeling system. Technical Report R-90-PM-01, CAM-I Inc., 1989.

[43] Jami Shah, Mary Rogers, Palat Sreevalsan, and Abraham Mathew. Functional requirement for the feature based modeling systems. Technical Report R-89-GM-01, CAM-I Inc., 1989.

[44] J. Sutherland and R. DeVor. An improved method for cutting force and surface error prediction in flexible end milling systems. *Transactions of the ASME, Journal of Engineering for Industry*, 108:269–279, 1986.

[45] J. Tlusty. Analysis of the state of research in cutting dynamics. *Annals of the CIRP*, 27(2):583–589, 1978.

[46] J. Tlusty and M. Elbestawi. Dynamic structural identification tasks and methods. *Annals of the CIRP*, 29(1):251–255, 1980.

[47] G. P. Turner and D. C. Anderson. An object oriented approach to interactive, feature based design for quick turn around manufacturing. In *ASME-computers in Engineering Conference*, San Fransisco, CA, July-Aug. 1988.

[48] Jan H. Vandenbrande. *Automatic Recognition of Machinable Features in Solid Models.* PhD thesis, Computer Science Department, UCLA, 1990.

[49] C. Vann and M. Cutkosky. Providing process histories for feedback from cam to cad. In *ASME Symposium on Advances in Integrated Product and Process Design*, November 1990.

[50] J.R. Woodwark. Generating wireframes from set-theoretic solid models by spatial division. *ACM*, 18(6), July/August 1986.

[51] S.M. Wu. Dynamic data system: A new modeling approach. *Transactions of the ASME, Journal of Engineering for Industry*, 1977.

[52] G.M. Zhang and T.W. Hwang. Analysis and control of geometric tolerancing through surface topography generation. In *Symposium on Automation of Manufacturing Processes, 1990 ASME Annual Meeting*, volume DSC-Vol. 22, pages 31–38, 1990.

[53] G.M. Zhang and T.W. Hwang. Analysis of the cutting dynamics in microscale. In *Symposium on Fundamental Issues in Machining, 1990 ASME Winter Annual Meeting*, volume PED-Vol. 43, pages 25–37, 1990.

[54] G.M. Zhang and T.W. Hwang. Process capability study in computerized manufacturing. In *Proceedings of the Fourth International Laboratory Information Management Systems Conference*, Pittsburgh, PA, June 1990.

[55] G.M. Zhang, T.W. Hwang, and G. Harhalakis. Control of surface topographies formed during machining. In *Proceedings of the Second International Conference on Computer Integrated Manufacturing*, pages 339–345, Troy, NY, May 1990.

[56] G.M. Zhang and S.G. Kapoor. Dynamic generation of the machined surface, part I: Mathematical description of the random excitation system. *Journal of Engineering for Industry, Transactions of the ASME*, May 1991.

[57] G.M. Zhang and S.G. Kapoor. Dynamic generation of the machined surface, part II: Mathematical description of the tool vibratory motion and construction of surface topography. *Journal of Engineering for Industry, Transactions of the ASME*, May 1991.

[58] G.M. Zhang and S. C-Y. Lu. An expert system framework for economic evaluation of machining operation planning. *Journal of the Operational Research Society*, 41(5):391–404, 1990.

[59] G.M. Zhang, S. Yerramareddy, S.M. Lee, and S.C-Y. Lu. Simulation of surface topography formed during the intermittent turning process. *Journal of Dynamic Systems, Measurement, and Control, Transactions of the ASME*, June 1991.

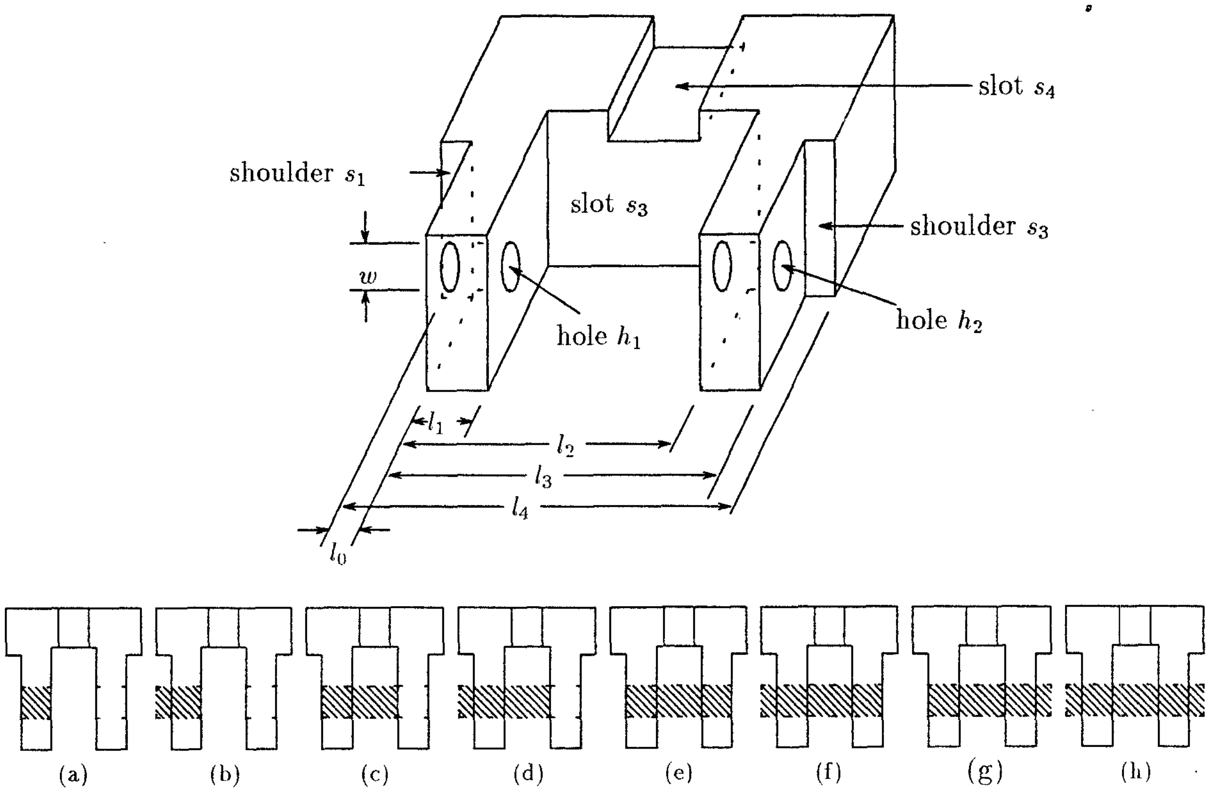

Figure 1: A bracket, and different interpretations of the hole h_1.

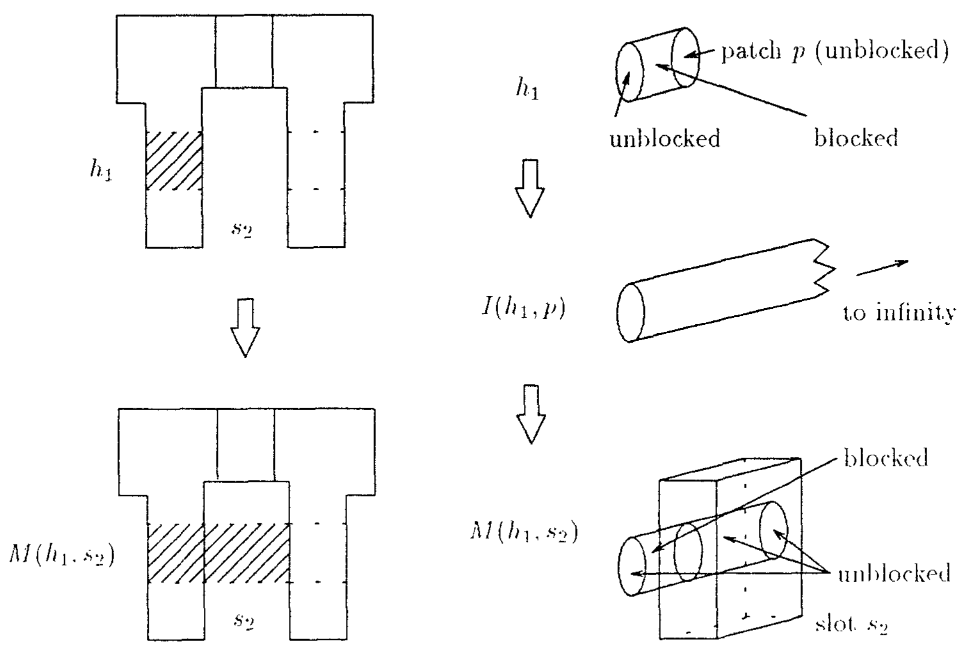

Figure 2: The maximal extension of h_1 into s_2.

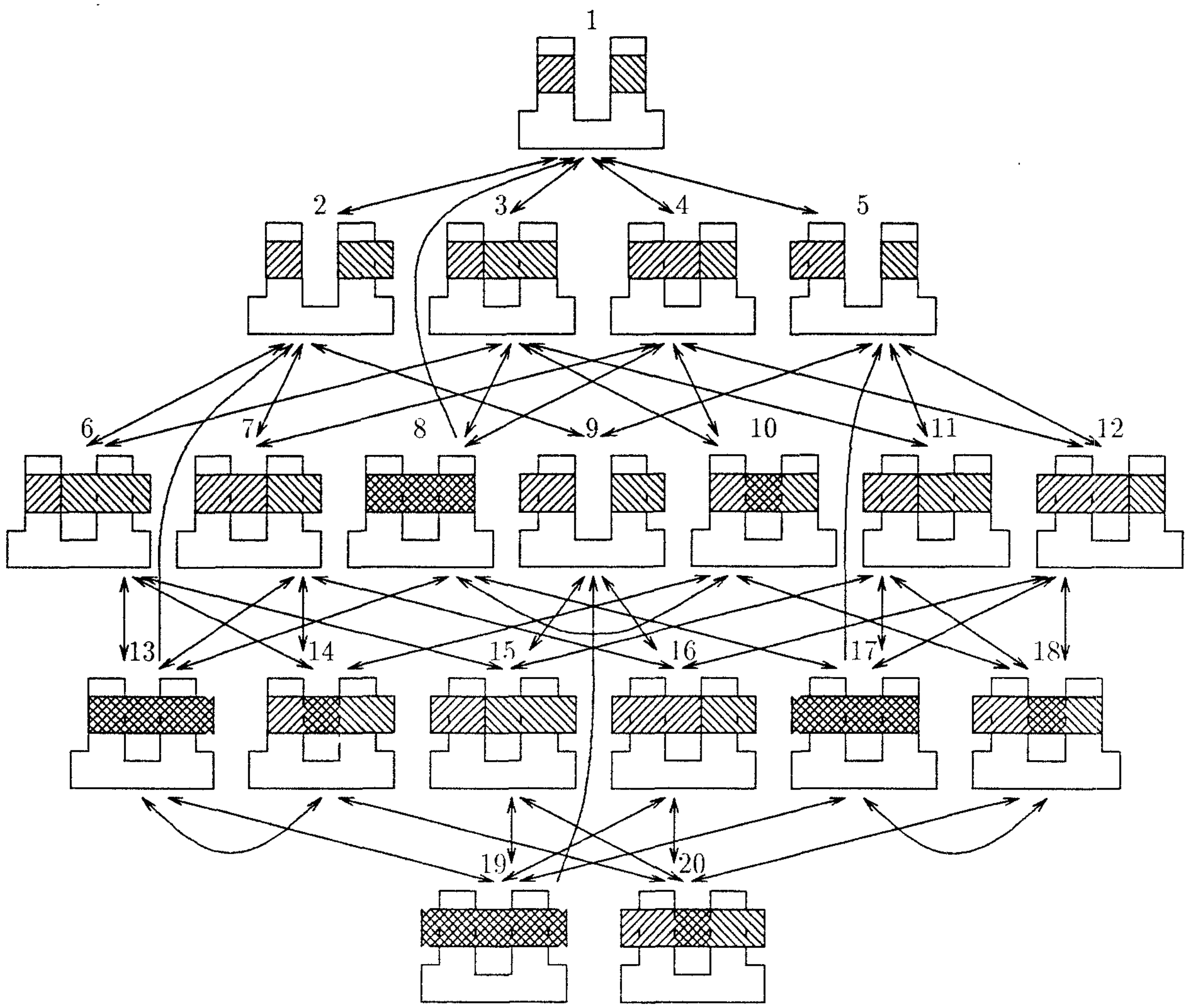

Figure 3: State space for operations on h_1, h_2, s_1, s_2, and s_3.

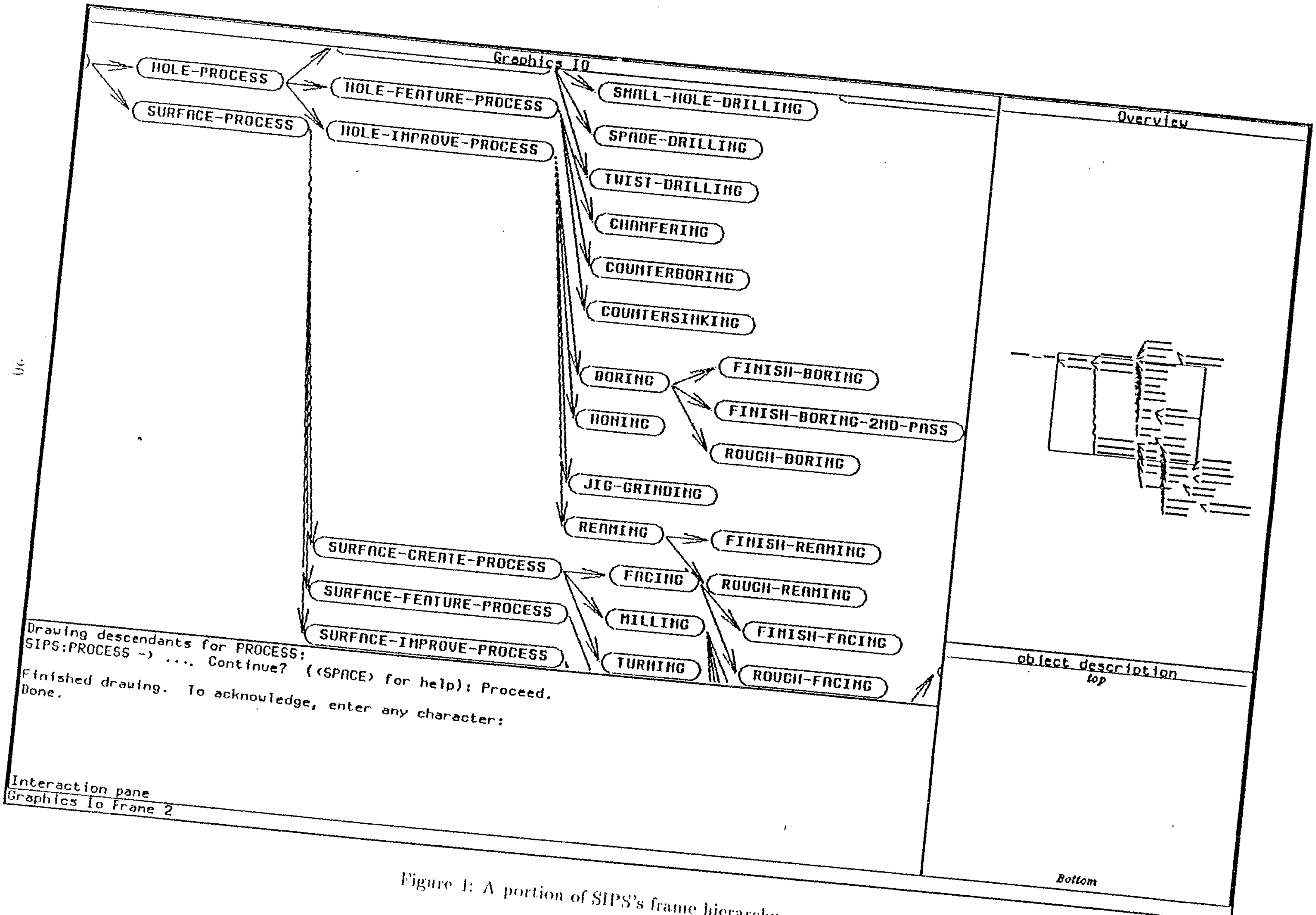

Figure 1: A portion of SIPS's frame hierarchy.

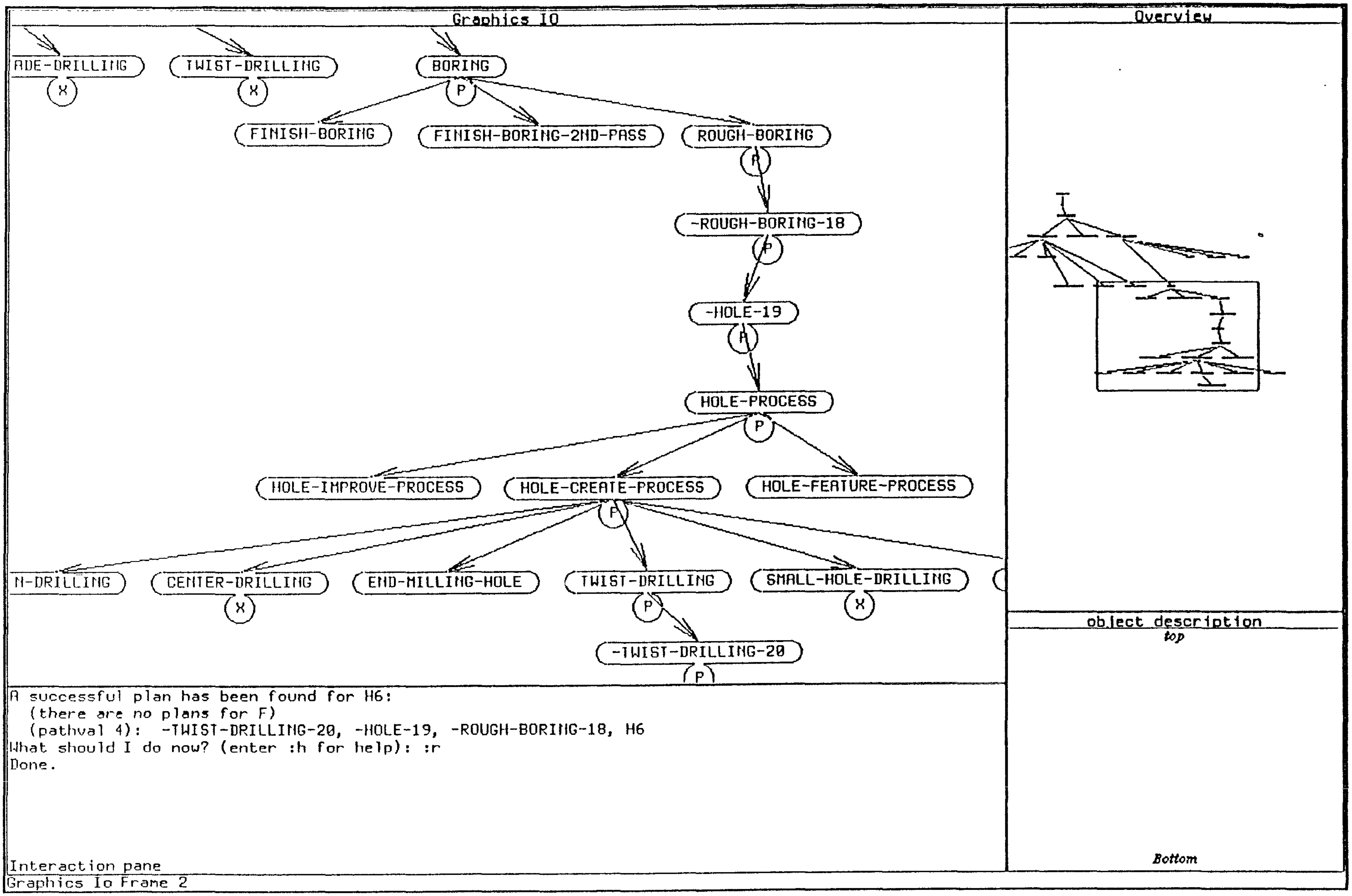

Figure 5: A search space generated by SIPS.

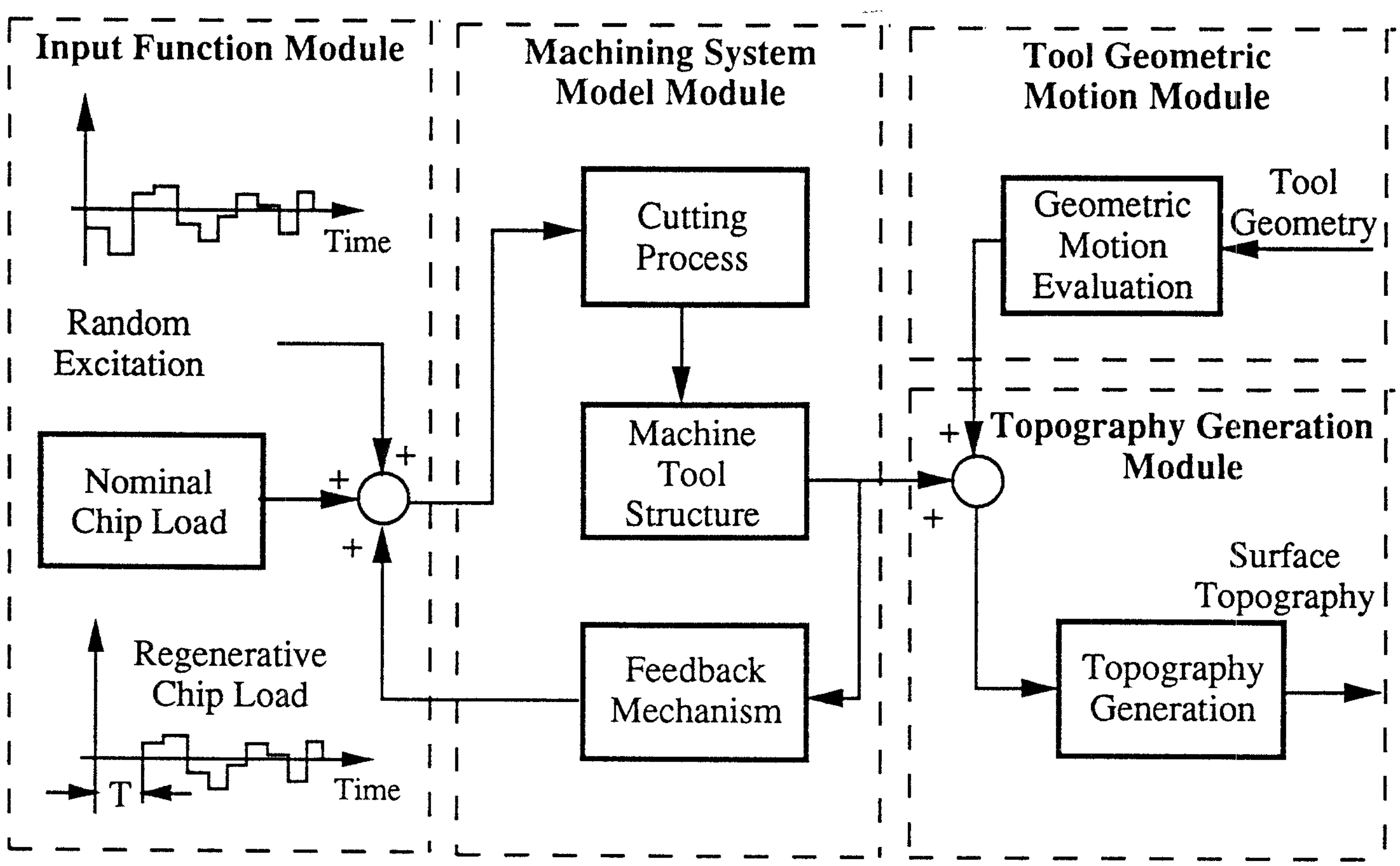

Figure 6: Methodology to simulate the Topography of a Machined Surface.

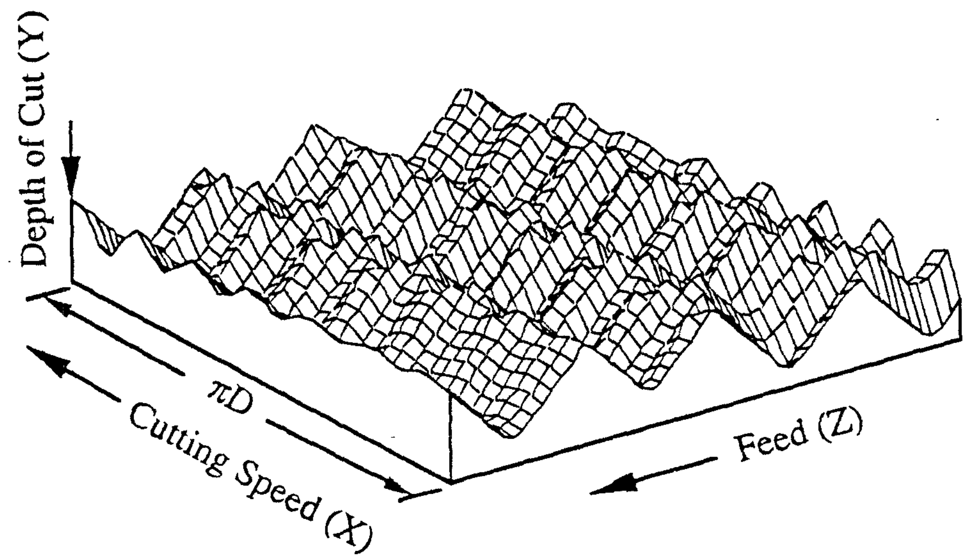

Figure 7: Simulated Surface Topography.

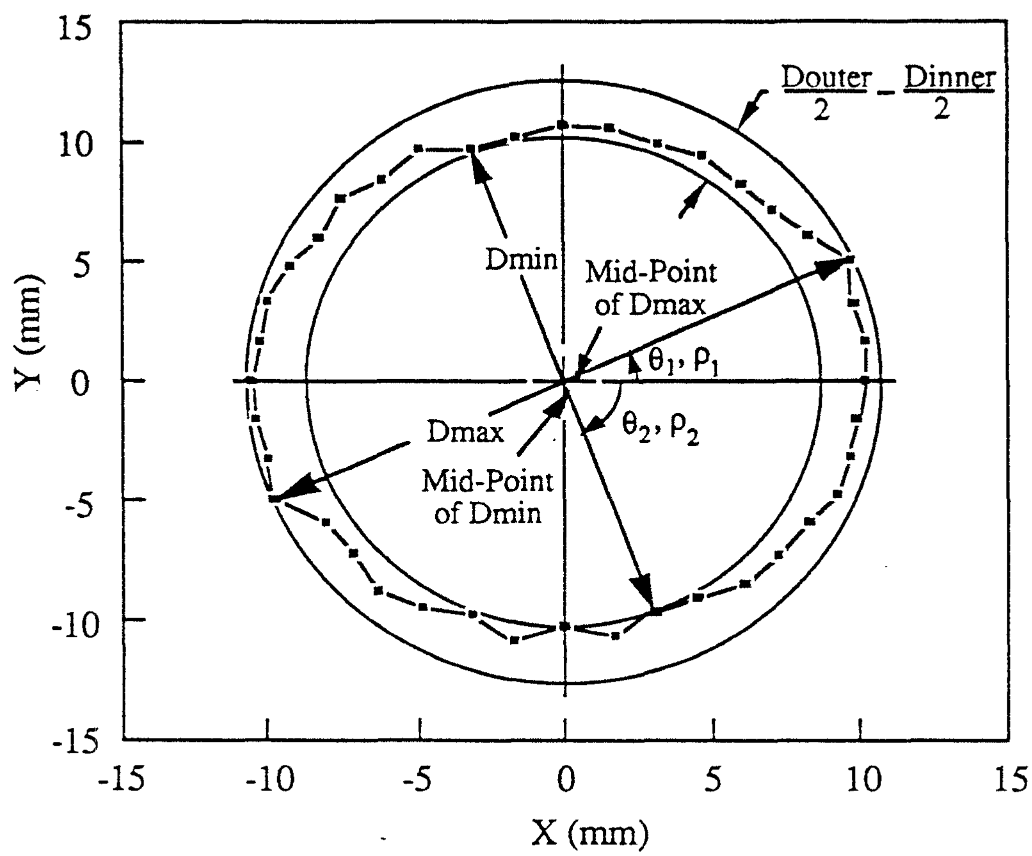

Figure 8: Contour of the Machined Surface at a Certain Cross-Section.

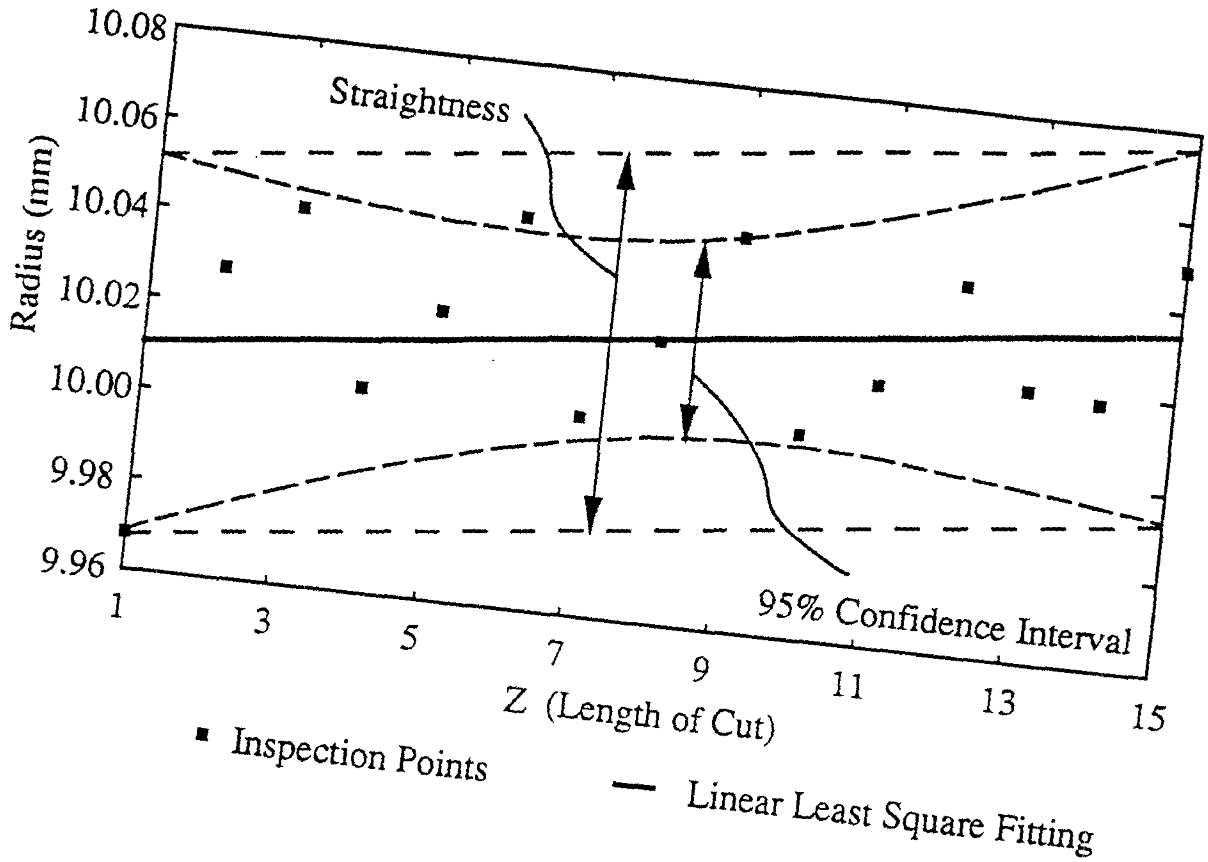

Figure 9: Straightness Estimation Based on Confidence Band.

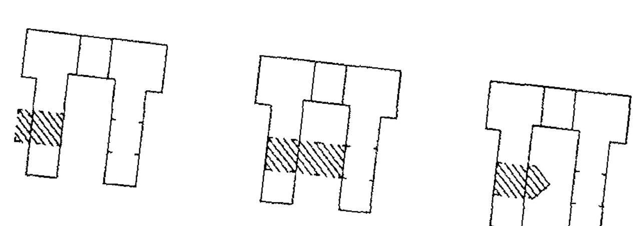

Figure 10: Interpretations (b) and (c), and how to machine interpretation (c).